

Construction and tests of a heart scanner based on superconducting sensors cooled by small stirling cryocoolers

A.P. Rijpma ^{a,*}, C.J.H.A. Blom ^b, A.P. Balena ^c, E. de Vries ^a, H.J. Holland ^a,
H.J.M. ter Brake ^a, H. Rogalla ^a

^a Low Temperature Division, Department of Applied Physics, University of Twente, P.O. Box 217, 7500 AE Enschede, Netherlands

^b Philips Medical Systems Nederland B.V., Afd. MR Scan Software, P.O. Box 10000, 5680 DA Best, Netherlands

^c Hollandse Signaalapparaten B.V., P.O. Box 42, 7550 GD Hengelo, Netherlands

Received 23 January 2001; accepted 16 February 2001

Abstract

At the University of Twente, a heart scanner has been designed and constructed that uses superconducting devices (superconducting quantum interference devices (SQUIDS)) to measure the magnetic field of the heart. A key feature is the elimination of liquid cryogens by incorporating cryocoolers. In the design, two coolers are operated in counter-phase to reduce the mechanical interference. In addition to the application of ferromagnetic shields around the compressors, the magnetic cooler interference is reduced by placing the SQUID magnetometers coplanar with respect to the coolers. In this way, the cooler noise was reduced to a level below the intrinsic sensor noise: 0.16 pT/ $\sqrt{\text{Hz}}$. A temperature of 60 K was realised with a cool-down time of about 2 h. The corresponding heat load to the coolers is roughly 0.9 W. Magnetocardiograms were recorded inside a magnetically shielded room. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Cryocooler; SQUID; Magnetic interference; Stirling cooler; Superconductivity

1. Introduction

Superconducting quantum interference devices (SQUIDS) are the most sensitive magnetic flux-to-voltage converting sensors. So far, their main application has been in biomagnetic research where multichannel low- T_c dc-SQUID based magnetometer systems are used. These systems are usually cooled by liquid helium and operated in magnetically shielded rooms to obtain an extremely low-noise measuring environment. Therefore, they are expensive, require cryogenic know-how and maintenance, and are fixed to a specific location.

Because of their higher operating temperature, a much more flexible magnetometer system can be realised with high- T_c SQUIDS. The ceramic copper oxides, as $\text{YBa}_2\text{Cu}_3\text{O}_7$ with a critical temperature $T_c \sim 92$ K, allow for SQUID operation in liquid nitrogen, boiling at 77 K. For cooling these high- T_c SQUIDS, also small-scale turnkey cryocoolers, originally developed for cooling

infrared sensors, are available [1]. The advantages of cryocoolers compared to liquid-nitrogen cryostats are the lower operating temperature, which gives a potentially better SQUID performance [2], and the turnkey operation.

In a previous paper [3], the design of a heart scanner has been presented that could be equipped with up to 25 high- T_c SQUIDS. This system is cooled by two small Stirling type cryocoolers. In the present paper, the actual construction and test experiments are presented. First, the design of the heart scanner is reviewed briefly. Then, the actual construction is considered followed by a section describing the test experiments. These concern cryogenic tests (cool-down temperature registration, heat load and operating temperature) and magnetometer tests (system noise level, magnetocardiography). The paper concludes with a discussion on the established results.

2. Heart scanner goals and design

The heart scanner system has been built to demonstrate the feasibility of cooling high- T_c SQUIDS by

* Corresponding author. Tel.: +31-53-4893841; fax: +31-53-4891099.

E-mail address: a.p.rijpma@tn.utwente.nl (A.P. Rijpma).

means of commercial cryocoolers. As an example, the system is applied to magnetocardiography, where the very small magnetic signals from the heart are to be measured.

2.1. Heart signal

The peak-to-peak amplitude of the magnetic signal of a human heart is determined by the amplitude of the so-called QRS-peak, which is its strongest component. This peak has an amplitude of typically 10–100 pT [4]. A spectral analysis of the heart beat reveals that most information is present in the 0.1–40 Hz range. However, to detect anomalies, frequencies up to 100 Hz should be considered. High- T_c SQUIDs can be applied to measure magnetocardiograms as we demonstrated in the past with a liquid-nitrogen cooled 7-channel system [5].

2.2. Cooling requirements

The primary requirement on the cooling system is that it reaches a temperature low enough for the sensors to be operational. This means that the SQUID sensors should be cooled to at least 80 K, which is not a difficult requirement to reach with contemporary coolers. Additionally, the contributions of the cooler to the system noise should be considered. These include direct contributions, such as mechanical and magnetic disturbances, as well as indirect contributions, such as temperature fluctuations. The latter is relevant as temperature fluctuations result in fluctuations of the sensor properties. As the influence of temperature fluctuations on the sensor properties decrease with decreasing temperature, temperatures as low as 60 K are preferred [2].

2.3. Design of the heart scanner

As the design considerations of the system are extensively described in a previous paper [3], this paper will only discuss the more relevant design aspects. As shown in Fig. 1, the core of the system is a $15 \times 15 \text{ cm}^2$ silicon plate, on which up to 25 high- T_c SQUID magnetometers may be mounted. This plate is located in a vacuum enclosure and cooled by two UP7058 Stirling cryocoolers [6,7]. These coolers have a specified cooling power of 1.5 W at 80 K for an input power of about 50 W. The coolers consist of an active compression unit and a passive cold-head separated by a so-called split-pipe of about 20 cm length. As the compressors are of the dual-opposed-piston-type, they intrinsically have a high mechanical balance. The cold-head vibrations are reduced by operating the two coolers in counter-phase. Next, to limit the magnetic interference from the compressors, they are placed at about 0.5 m from the sensors. Moreover, their orientation relative to the SQUID sensors is such that the magnetic field from the drive

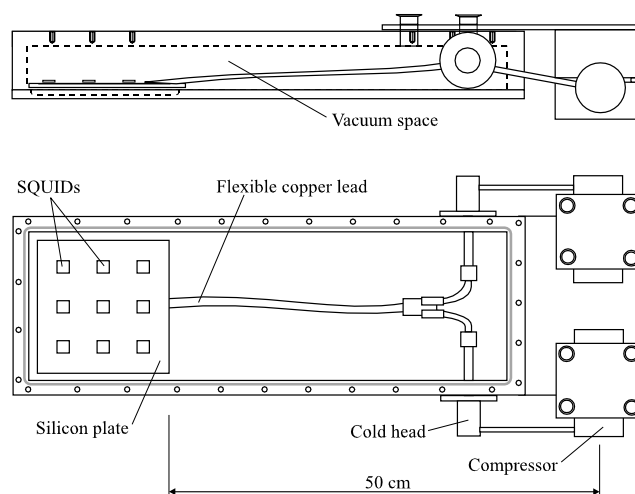


Fig. 1. Heart scanner design (schematic), depicted with nine SQUIDs: side view and bottom view.

currents is parallel to the silicon plate and thus orthogonal to the sensors' axes of sensitivity. Due to the spatial separation, flexible copper leads are required to thermally connect the silicon SQUID plate to the cold tips of the coolers.

3. Heart scanner construction

3.1. Vacuum box

The vacuum box is manufactured from 17 mm thick glass-fibre reinforced epoxy plates (G10). The box is closed by means of nylon screws and sealed with a viton O-ring. The cover has a thickness of only 10 mm. In order to minimise the distance of the SQUIDs to the outside even further, a section of $17 \times 17 \text{ cm}^2$, directly facing the silicon SQUID plate, is reduced to a 5 mm thickness. Two flanges are glued into the box: one for vacuum pumping, the other for wiring. In order to maintain proper vacuum, activated carbon is placed on the cold tips and on the thermal link to serve as getter material.

3.2. Heat sinking

As the performance of the coolers decreases significantly with increasing warm-end temperatures, proper heat sinking is very important. In that respect, convective cooling by means of a forced water or air flow is very attractive. However, for simplicity it was decided to rely on free-convection cooling using a heat sink. For that purpose, the coolers are mounted on an aluminium plate to which also a heat sink is attached. This construction is depicted in Fig. 2. The compressors are clamped in aluminium blocks that are rigidly mounted on the aluminium plate. The latter is about $30 \times 36 \text{ cm}^2$

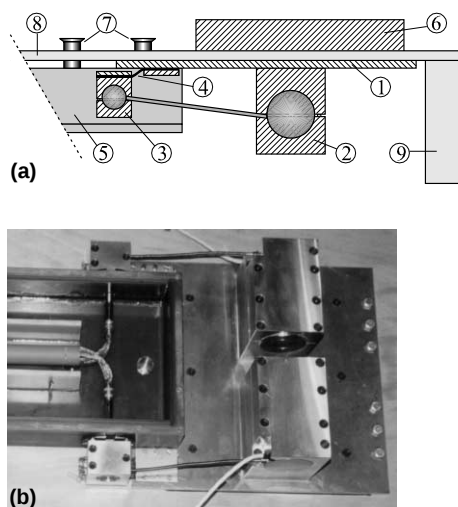


Fig. 2. Heart scanner assembly: (a) Schematic drawing: 1: aluminium mounting plate; 2: aluminium compressor blocks; 3: aluminium cold-head blocks; 4: "flexible" heat link; 5: glass-epoxy vacuum box; 6: heat sink; 7: flanges for pump and wire feedthroughs; 8: wooden base plate; 9: wooden support. (b) Photograph.

in size and 8 mm thick. On the other side of this plate a $30 \times 25 \text{ cm}^2$ high-power extrusion heat sink of Therm-alloy [8] is attached (type S245). The mounting plate is mechanically fixed to the glass-epoxy vacuum box. Therefore, in order not to compromise the O-ring vacuum seals between cold-heads and the vacuum box, the cold-heads cannot be rigidly mounted on the aluminium plate. Instead, a flexible link has to be applied between the cold-heads and plate, resulting in an additional thermal resistance between cold-head and heat sink. Per cold-head 12 aluminium strips are used with a width of 24 mm and a thickness of 0.5 mm. The contact area on the cold-head side is about 10 cm^2 , that on the plate 12 cm^2 . The length in between the contacts is 11 mm. At all interfaces alumina-filled grease is applied to improve the thermal contact.

3.3. Thermal link

The thermal link from the cold tips to the SQUID plate is made of two Litze-cables consisting of separate twisted and non-insulated copper wires. Each cable has a cross-sectional area of 20 mm^2 and a length of 30 cm. A conically shaped copper cap is soldered onto that end of each cable that is attached to the cold tip of a cold-head. The other ends of the cables are soldered onto copper plates that are clamped to the silicon SQUID plate. At both ends copper-filled grease is applied to improve the thermal contact. To prevent the copper leads from touching the sides of the vacuum box, they are led through a G10 tube as can be seen in Figs. 2 and 3. At both ends of the tube, nylon wires are used to suspend it between two supporting G10 plates.

3.4. SQUID sensors

Two SQUID sensors are available, which were previously used in the development of the 7-channel liquid-nitrogen cooled system [5]. The intrinsic noise of these SQUIDs is about $0.16 \text{ pT}/\sqrt{\text{Hz}}$. These SQUIDs are packaged in alumina chip carriers to protect them from moisture. As only two SQUIDs are used in the test experiments the silicon plate can be limited in size to $4 \times 15 \text{ cm}^2$ (thickness 0.7 mm). The SQUID packages are glued onto the plate by means of GE varnish [9]. The modulation coils are mounted on the reverse side of the plate. The centre of the first SQUID is 5.5 cm from the copper thermal link, the centre of the second SQUID 11.9 cm.

3.5. SQUID plate

The position of the SQUID plate inside the vacuum box is fixed by means of glass spacers. These were machined in a tetrahedral shape, three short ones with a height of 10 mm to be used at the SQUID side of the silicon plate, and three long ones of 48 mm for the other side. All were machined with a contact area of about 10^{-2} mm^2 at the top. At the base, the short ones have a contact area of 16 mm^2 , the long ones 65 mm^2 . In order to prevent the silicon plate from breaking because of the spacer forces, small G10 strips are glued onto the plate for distributing the forces over it. Furthermore, small disks of silicon rubber with a thickness of 1.2 mm are placed between the spacers and the G10 box to allow for some spacer flexibility.

3.6. Wiring

Each SQUID requires eight connecting wires. Except for the two signal lines these can be resistive. We, therefore, use twisted pairs of manganin wire [10]. The signal lines are made with twisted pairs of 0.15 mm diameter copper wire. To reduce the conductive heat load through the wires, 30 cm long wires are used between the feedthrough flange on the vacuum box and the cold tips where the wires are thermally anchored. The extra length of wire is wound around a kapton cylinder in the vacuum space. From the cold tips to the SQUIDs the lines each have a length of about 50 cm.

3.7. Multilayer insulation

The radiative heat flows to the SQUID plate, the thermal link and the cold fingers are reduced by 15 layers of aluminised mylar foil, MLI type NRC-2 [9]. As it is not possible to wrap the complete cryogenic part with a single sheet, we use 15 separate pieces that are folded one over the other. First, 15 sheets are placed in the box. The glass spacers, which support the silicon



Fig. 3. Photograph of the vacuum box (from left to right): the silicon SQUID plate supported by three glass spacers, the thermal link held inside a G10 tube, and the cold fingers coaxially mounted on the box with a heat sink surrounding the warm-ends. Note that in comparison with the side view in Fig. 1 the vacuum box is upside-down.

plate prick through these sheets. Next, the G10 support tube, the copper leads of the thermal link and the SQUID plate are put in position. After that, the MLI sheets are folded to close the MLI blanket. Finally, the lid is put on the vacuum box. At the same time, the three glass spacers in the lid pierce the MLI blanket, thus fixing the SQUID plate's position within the box.

3.8. Thermometry

The temperatures of the compressors, the cold-head warm-ends, the cold tips, the copper link and the SQUID plate are recorded with Lake Shore diodes, specified accuracy ± 1.5 K or 1.5% [10]. The diodes are glued in place with GE varnish [9]. The temperature diodes are connected in series and a current of 10 μ A is supplied. Both for supplying the current as well as for recording the output voltages of the diodes, manganin wire is used.

4. Thermodynamic considerations

4.1. Warm-end temperatures

The cooling power available at the cold tip of a cooler depends on the input power, the temperature of the cold tip and the environmental temperature. The latter dependence is mostly due to the displacer warm-end temperature. For example, at 55 W input power and 80 K operating temperature, a warm-end temperature increase of 10 K gives a decrease in cooling power of 0.15 W [7].

A rough thermodynamic model is made to estimate the warm-end temperatures. Firstly, it assumes the mounting plate to be at uniform temperature and secondly, all heat rejection to the environment to take place at the heat sink only. Then, a thermal node model is formed with the compressors, the cold-heads' warm-ends, the mounting plate and the heat sink as nodes and the environment as a thermodynamic ground. Roughly

one third of the total cooler input power is dissipated in the cold-head. A substantial part of this heat is caused by the surface heat pumping mechanism in the split-pipe [11]. Starting with an environmental temperature of 294 K (21°C), the following temperatures result from the analysis: plate 320 K, compressors 321 K, cold-heads 329 K. The margin of error in these temperatures is a few Kelvin.

4.2. Heat load

To find the SQUID plate temperature, the heat load to the system should be known. Two heat load terms are relevant. Firstly, the heat load through the vacuum space and the MLI blanket and secondly, the conductive heat flow through spacers and wires.

Especially near the spacers, the sheets will be more or less pressed together. Furthermore, we have used separate sheets that were folded to close the blanket. That means a lot of openings are present in the blanket that result in a higher heat flow. Therefore, a worst-case limit is considered. As the emissivity ϵ_{MLI} of the MLI blanket is small compared to that of the G10 box, the heat flow from the box to the MLI can be expressed as:

$$\dot{Q}_{\text{vac}} = \epsilon_{\text{MLI}} A_{\text{MLI}} \sigma (T_{\text{out}}^4 - T_{\text{MLI}}^4), \quad (1)$$

where A_{MLI} and T_{MLI} are the outside surface area and temperature of the MLI blanket, respectively. T_{out} is the temperature of the G10 box. In the worst-case, the MLI layers have so much thermal contact that the temperature T_{MLI} of the outer layer equals the temperature of the SQUID plate. In that case, the term T_{MLI}^4 in Eq. (1) can be neglected. With $A_{\text{MLI}} = 0.1$ m², $\epsilon_{\text{MLI}} = 0.034$ [12] and $T_{\text{out}} = 295$ K the resulting heat flow is 1.5 W.

The heat flow through the spacers and the wires is less important. Neglecting the thermal resistances at the contact interfaces, we estimated this flow to be around 60 mW, mostly due to the spacers. These flows do not add significantly to the 1.5 W that was calculated above.

Table 1
Magnetic noise from metal objects

	T (K)	σ (S)	A_x (m ²)	x_0 (m)	$x_0 + l$ (m)	Noise (fT/ $\sqrt{\text{Hz}}$)
Displacer	329	3.7×10^7	25×10^{-4}	0.34	0.38	6
Compressor	321	3.7×10^7	1.2×10^{-2}	0.53	0.61	7
Base plate	320	3.7×10^7	24×10^{-4}	0.35	0.71	9
Heat sink	320	3.7×10^7	1.4×10^{-2}	0.43	0.68	15
Thermal link	60	8.3×10^9	40×10^{-6}	0.055	0.36	41

4.3. SQUID plate temperature

The SQUID plate temperature follows from a balance between the above-evaluated heat load and the available cooling power. Van den Bosch [3] reported a cooler performance of

$$P_{\text{in}} = 53 \text{ W}, \quad T_{\text{ch}} = 323 \text{ K} : \dot{Q}_{\text{C}} = a(T_{\text{tip}} - T_{\text{min}}); \quad (2)$$

$$a = 0.04 \text{ W K}^{-1}; \quad T_{\text{min}} = 43.3 \text{ K}.$$

After correcting for the slightly higher input power and reducing the cooling power with 0.02 W K^{-1} [13] due to the higher cold-head temperature T_{ch} , we obtain

$$P_{\text{in}} = 55 \text{ W} : \dot{Q}_{\text{C}} = a_1(T_{\text{tip}} - T_{\text{min}}) - a_2(T_{\text{ch}} - T_{\text{ref}}), \quad (3)$$

$$a_1 = 0.0415 \text{ W K}^{-1}; \quad T_{\text{min}} = 43.3 \text{ K};$$

$$a_2 = 0.02 \text{ W K}^{-1}; \quad T_{\text{ref}} = 323.2 \text{ K}.$$

Doubling this power to account for two coolers and combining it with the estimated heat load, this leads to a temperature of 65 K at the coolers cold tip.

The temperature rise over the thermal link from the cold tips to the SQUIDS can be evaluated by assuming the total heat load $\dot{Q}_{\text{L}}$ to be equally distributed over the length L of the link. In that case the temperature rise is given by

$$T_{\text{SQUID}} - T_{\text{tip}} = \frac{1}{2} \frac{L}{\lambda A} \dot{Q}_{\text{L}}. \quad (4)$$

Here, A is the cross-sectional area of the link and λ its thermal conductivity. The thermal resistance $L/(\lambda A)$ of the link is evaluated as 11 K W^{-1} . Eq. (4) then yields a SQUID temperature of 73 K.

4.4. Magnetic noise

In the design, special attention was paid to the thermal magnetic noise contribution from the material of the heat sink. This should be significantly less than the SQUID noise level. The thermal noise contribution of the heat sink material can be evaluated by considering small volume elements dV . The thermal noise current density in this element is uniformly distributed in all directions and its effective amplitude is given by [14]

$$j_{\text{RMS}} = \sqrt{4kT\sigma\Delta f/dV}. \quad (5)$$

Here, T is the temperature of the material, σ its electrical conductivity and Δf the frequency bandwidth. Consider

the SQUID to be placed in the origin of the co-ordinate system with its normal in the z -direction (i.e., the SQUID senses the z -component of the magnetic field). Next, consider a metallic object. Then the thermal noise contribution of the plate can be evaluated by means of Eq. (5) and the Biot–Savart law. Assuming the object (height h , width w , length l) to lie along the x -axis at a distance x_0 from the nearest SQUID sensor, the following approximation is obtained in case both $h \ll x_0$ and $w \ll x_0$:

$$S_{\text{B}}^{1/2} = \sqrt{\frac{B_n^2}{\Delta f}} = \frac{\mu_0}{4\pi} \sqrt{kT\sigma A_x(x_0^{-3} - (x_0 + l)^{-3})}, \quad (6)$$

where $A_x = hw$. If h or w is not small compared to x_0 , Eq. (6) is still a useful worst-case estimate.

Based on Eq. (6) the thermal noise contribution of the metallic components is evaluated (Table 1). The dominant contribution in the present design is from the copper link. In our construction, the distance from the SQUID to the lead is 5.5 cm, resulting in a noise contribution of 41 fT/ $\sqrt{\text{Hz}}$. This is sufficiently below the noise level of the current SQUIDS but once improved SQUID sensors are available, the noise from the link should be reduced. This may, for example, be achieved by replacing the last centimetres of the link by sapphire.

5. Experiments

5.1. Vacuum test

An important parameter in the heat flow through an MLI blanket is the residual gas pressure. Thermal conduction via the gas becomes a relevant heat flow contribution when the pressure in the vacuum space rises above about 10 mPa [15]. In our tests we pumped the vacuum box to 3 mPa. After the pump was switched off, the pressure rose to 40 mPa. At that time, the coolers were started and the pressure dropped to 1.8 mPa because of the carbon getter.

5.2. Cryogenic test

A recording of the system cool-down is shown in Fig. 4. The coolers were started at $t = 10$ min and their input powers were increased to 55 W in the following

3 min. After about 90 min of cooling, the temperature of the SQUID plate decreased less than 0.1 K per minute. At $t = 105$ min, the cold-heads' warm-ends had reached a temperature of 330 and 334 K (cold-head 1 and 2, respectively). Both compressors were at 319 K. These temperatures are roughly in agreement with the thermal node model.

The SQUID plate had cooled to 64 K with tip 2 at 59 K. Taking into account the measuring accuracy of the cold tip temperature and Eq. (3) the total cooling power is 0.95 ± 0.2 W. Following Eq. (4) this results in a SQUID temperature of 64 ± 2 K, which corresponds to the measured data. A comparison of these data with the previously calculated temperatures and heat loads shows that we are at about two-thirds of the estimated worst-case heat load. This means that the layers make so much contact that we are only slightly better off than with just one layer of MLI. Therefore, lowering the amount of layers should not significantly increase the heat load. Indeed, when we closed the system later with only three layers, only a slightly higher heat load was observed (1.2 ± 0.4 W).

To illustrate the importance of the cooler cold-head temperature, a fan was switched on at $t = 106$ min to actively cool the warm-end of cold-head 2. As a result, the warm-end temperature decreased by 9 to 325 K. The SQUID plate cooled down further to 59.4 K, with tip 2 at 55.9 K.

5.3. SQUID magnetometer experiments

After the SQUIDs were mounted, the system was placed in the magnetically shielded room of the Bio-magnetic Centre Twente. Unfortunately, one of the SQUIDs that we used displayed a continuous loss of

performance in time. Quite steadily the critical current had decreased and so had the required operating temperature. During our experiments, the operating temperature of this SQUID was so low (<68 K) that it could not be operated simultaneously with the other SQUID that functioned properly at higher temperatures. Therefore, the test experiments were performed with the latter SQUID only.

First, the cooler interference at the operating frequency of 50 Hz was measured to be $50 \text{ nT}_{\text{RMS}}$. This is significantly more than the design limit of $10 \text{ nT}_{\text{RMS}}$ [3]. Therefore, further suppression of the 50 Hz peak was required and was realised later by means of mu-metal shielding. Second, the noise spectrum was measured as depicted in Fig. 5(a). Here, we had to apply an analogue 50 Hz notch filter to limit the required dynamic range of the acquisition system. Except for the remaining noise peaks resulting from the 50 Hz interference, the noise level from 10 to 100 Hz was $4.2 \text{ pT}/\sqrt{\text{Hz}}$. When the coolers were switched off, the noise level dropped to about $0.16 \text{ pT}/\sqrt{\text{Hz}}$ (Fig. 5(c)). Because of the temperature drift in this case, the noise level at lower frequencies was higher. At 10 Hz the noise level was $0.24 \text{ pT}/\sqrt{\text{Hz}}$ in this experiment. The higher white noise level with the coolers running was mostly due to noise in the compressor currents. These currents are generated by computer and set to adequate powers by means of audio amplifiers [16,17]. In these circuits apparently a small thermal noise contribution is added to the 50 Hz drive currents. Whereas the 50 Hz currents for the four different compressor coils are correlated and tuned in such a way that they counter-act [3], the thermal noise introduced by the amplifiers is not correlated. Therefore, the noise powers add up. To deal with this noise, it was decided to adapt the aluminium blocks holding the

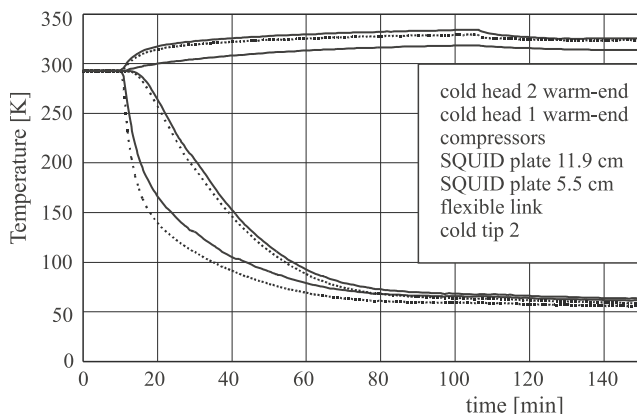


Fig. 4. Cool-down temperature registration. Upper curves from top to bottom: solid: cold-head 2, warm-end; dashed: cold-head 1, warm-end; solid: compressors (1 and 2); dashed: heat-sink mounting plate. Lower curves from top to bottom: solid: SQUID plate at 11.9 cm from link; dashed: SQUID plate at 5.5 cm from link; solid: thermal link; dashed: cold-head 2, cold tip.

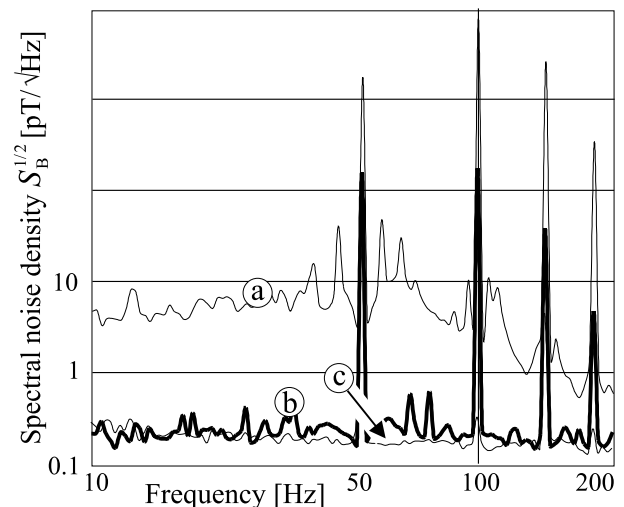


Fig. 5. Magnetic field noise spectra measured by high- T_c SQUID: (a) no magnetic shielding; (b) magnetic shielding around the compressors; (c) coolers off.

compressors in such a way that the compressors could be completely covered by mu-metal shields. In previous experiments we have measured a shielding factor of 40 for such cans [18]. By means of this shielding of the compressors, we were able to reduce the noise to the level recorded with the coolers off, i.e. $0.16 \text{ pT}/\sqrt{\text{Hz}}$, see Fig. 5(b). As mentioned above, the 50 Hz noise peak was also significantly reduced because of the magnetic shielding.

In this set up we recorded magnetocardiograms of adults such as shown in Fig. 6. For this purpose, we used an analogue 50 Hz notch filter and a digital 0.1 Hz high-pass filter, 100 Hz low-pass filter and 50 Hz notch filter (49.4–50.6 Hz). In the unaveraged MCG data of Fig. 6, all relevant peaks can be distinguished: the P-wave and the QRS-complex, respectively, due to the depolarisation of the atria and that of the ventricles, and the T-wave resulting from the repolarisation of the ventricles [19].

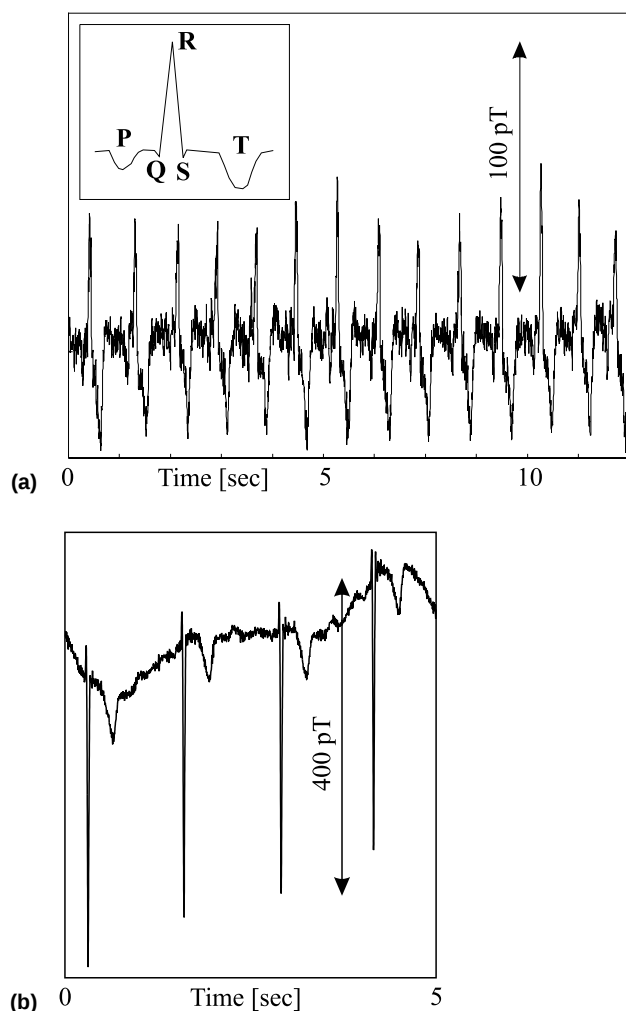


Fig. 6. Magnetocardiograms recorded with the heart scanner system (applied filters: 0.1–100 Hz band-pass, 50 Hz notch): (a) subject 1; inset: schematic of MCG-features; (b) subject 2.

6. Discussion

A cryogen-free high- T_c SQUID-based heart magnetometer was built and successfully tested. A SQUID plate temperature of 60 K was realised in about 2 h. With a high- T_c SQUID, a noise level of $0.16 \text{ pT}/\sqrt{\text{Hz}}$ was measured in the frequency band 10–100 Hz and magnetocardiograms were recorded inside a magnetically shielded room. The next step in this development will be the incorporation of multiple SQUIDs. By electronically combining the outputs of these SQUIDs, a gradiometer can be realised [20]. Then, the system can be tested outside the magnetically shielded room.

The initial white noise contribution of the audio amplifiers to the magnetic field, was not anticipated. This was solved by placing mu-metal shields around the compressors. Afterwards, the coolers only added to the intrinsic SQUID noise at their drive frequency 50 Hz, which is acceptable. However, because this shielding distorts environmental magnetic fields, it may cause problems when the system is operated in an unshielded environment. Therefore, a more elegant way to solve the problem of the compressor noise currents may be to use one power supply to drive both pistons of one cooler. This would be the standard operation for the coolers and we deviated from this in order to reduce the mechanical vibrations originating from the coolers [16,17]. However, magnetic balancing may turn out to be more important than mechanical balancing.

Towards clinical application, the cryogenic construction can be improved. Firstly, this concerns the glue connections that are made with GE-varnish. Especially, the glue connections on the silicon plate appeared to have poor reliability. Secondly, the glass spacers are quite vulnerable. Suspension of the silicon plate by means of wraps or nylon wires will work much better. Finally, the radiation shielding can be improved. This would allow for smaller coolers or lower operating temperatures.

Acknowledgements

We are indebted to P.J. van den Bosch, H.A. de Boer, and W.A.M. Aarnink for their contributions in the cryogenic design of the system. Also, J.F.C. Verberne is acknowledged for his contribution on the cooler noise suppression, and H.W.M. Veldhuis for the realisation of the glass-epoxy vacuum box. Further, we thank Signaal USFA for the support and the fruitful contributions in the discussions: a special word of thanks in this respect to A.A.J. Benschop and P.C. Bruins. The research was also financially supported by the Dutch Research Program on high- T_c Superconductors (NWO/NOP – HT $_c$) and the Dutch Technology Foundation (STW).

References

- [1] Walker G. Miniature refrigerators for cryogenic sensors and cold electronics: monographs on cryogenics, vol. 6. Oxford, UK: Clarendon Press; 1989.
- [2] Rogalla H. Superconducting electronics. *Cryogenics* 1994;34:25–30.
- [3] van den Bosch PJ, ter Brake HJM, Holland HJ, de Boer HA, Verberne JFC, Rogalla H. Cryogenic design of a high- T_c SQUID-based heart scanner cooled by small Stirling cryocoolers. *Cryogenics* 1997;37:139–51.
- [4] Katila T, Karp P. Magnetocardiography: morphology and multipole representations. In: Williamson SJ et al., editors. Biomagnetism, an interdisciplinary approach. New York: Plenum Press; 1983. p. 237–63.
- [5] ter Brake HJM, Karunanithi R, Holland HJ, Flokstra J, Veldhuis D, Vargas L, Hilgenkamp JWM, Jaszczuk W, Janssen N, Roesthuis FJG, Rogalla H. A seven-channel high- T_c SQUID-based heart scanner. *Meas Sci Technol* 1997;8:927–31.
- [6] Signaal USFA, P.O. Box 6034, 5600 HA, Eindhoven, The Netherlands.
- [7] Verbeek D, Helmonds H, Roos P. Performance of the Signaal USFA Stirling cooling engines. In: Proceedings of the Seventh International Cryocooler Conference. Santa Fe; 1993. p. 728–37.
- [8] Thermalloy, Inc. P.O. Box 810839, Dallas TX 75381-0839, USA.
- [9] GE low-temperature varnish and superinsulation NRC-2 were supplied by Oxford Instruments, Eynsham, Oxford OX8 1TL, England.
- [10] Silicon diode temperature sensors (types DT-470/471-LR) and manganin high-resistance wire (type MW-36) were supplied by Lake Shore Cryotronics, Westerville, OH, USA.
- [11] Benschop AAJ, van Wordragen FC, Bruins PC. Reduction of surface heat pumping effect in split-Stirling cryocoolers. In: *Cryocoolers 9*. New York: Plenum Press; 1997. p. 139–46.
- [12] ter Brake HJM, Flokstra J. Computer aided cryostat design in Twente: recent developments. In: Scurlock RG, Bailey CA, editors. Proceedings of the 12th International Cryogenic Engineering Conference. Guildford, UK: Butterworth; 1988. p. 88–92.
- [13] Bruins PC, Signaal USFA, personal communication.
- [14] Bakker CJ, Heller G. On the Brownian motion in electric resistances. *Physica* 1939;6:262–74.
- [15] Scurlock RG, Saul B. Development of multilayer insulations with thermal conductivities below $0.1 \mu\text{W cm}^{-1} \text{K}^{-1}$. *Cryogenics* 1976;16:303–11.
- [16] Rijpma AP, Verberne JFC, Witbreuk EHR, Bruins PC, ter Brake HJM. Adaptive periodic disturbance cancellation in a set-up of two cryocoolers. *J Sound Vib* 1998;217(3):419–34.
- [17] Rijpma AP, Verberne JFC, Witbreuk EHR, ter Brake HJM. Vibration reduction in a set-up of two split type Stirling cryocoolers. In: *Cryocoolers 9*. New York: Plenum Press; 1997. p. 727–36.
- [18] ter Brake HJM, Aarnink WAM, van den Bosch PJ, Hilgenkamp JWM, Flokstra J, Rogalla H. Temperature dependence of the effective sensing area of high- T_c dc SQUIDS. *Supercond Sci Technol* 1997;10:512–5.
- [19] Ern  SN, Lehmann J. Magnetocardiography, an introduction. In: *SQUID sensors: fundamentals, fabrication and applications*. Dordrecht: Kluwer Academic Publishers; 1996. p. 395–412.
- [20] Vrba J. Multichannel SQUID biomagnetic systems. In: Weinstock H, editor. *Applications of superconductivity*. Dordrecht: Kluwer Academic Publishers; 2000. p. 139–228.